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RADAR ABSORBING MATERIALS – MECHANISMS AND MATERIALS

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ABSTRACT

This Report gives an introduction to the theoretical basis for the design of radar absorbing materials (RAM) with emphasis given to techniques for modifying material properties to give the desired performance. These techniques include additives in the form of scatterers, loops, antennae and graded absorbers. A brief survey of the more common types of commercially available radar absorbing material is given. Experimental methods for measuring and testing these materials are described.

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RADAR ABSORBING MATERIALS - MECHANISMS AND MATERIALS

1. INTRODUCTION

The development of radar systems before and during the Second World War lead to investigations of the interaction between electromagnetic radiation at radar frequencies and various materials; one aspect of these investigations being to find ways of reducing the returned signal. This was undertaken not only to reduce interference between the radar signal and surrounding structures (e.g. radar masts, towers, support buildings which could degrade the performance of one's own radar), but also to help reduce detection by hostile radars by means of suitably designed anechoic materials. The Germans developed coatings for their submarine periscopes, snorkels and conning towers which achieved a reflection decrease of almost 26 db in the 112 to 195 cm wavelength band [1]. A number of physical shortcomings however, mainly the coating's lack of survivability in harsh environments, prevented the large scale implementation and deployment of this material.

Since the Second World War, there has been increasing interest in Radar Absorbing Materials (RAM), culminating in the American "stealth" projects for the Advanced Technology Bomber and Advanced Technology Fighter [2] and the deployment of RAM on Naval vessels. These developments have been based on a synergystic approach, the reduction in radar cross section being obtained by a number of complementary methods. The primary techniques employed are radar absorbent structures, radar transparent structures, modification of geometrical shape and the use of radar absorbing materials as surface coatings. The application of these concepts to all types of defence materiel is most important. The increasing use of radars in battlefield surveillance and weapon homing, in addition to the traditional air-target detection role, means that improved techniques for radar camouflage and countersurveillance must be developed and deployed for all types of equipment.

For existing material, the application of radar cross-section reduction techniques could involve radical structural modification, and in some cases might not be justifiable in terms of performance or cost. However, the selective use of thin radar absorbent coatings applied to existing material can, in the right circumstances, provide real benefit in terms of performance and cost-effectiveness.

To gain some qualitative insight into the benefits that may be achieved by reducing the radar cross section of material, an examination of the classic free space radar range equation is instructive [6]. This equation has the form

$$P_r = P_t \frac{G^2 \lambda^2}{(4\pi)^3} \frac{\sigma}{R^4}$$

where P_r and P_t are the powers received and transmitted by the antenna respectively, G is the antenna gain, R is the detection range, λ is the wavelength and σ is the radar cross section.

The equation shows that the detection range varies as the fourth root of the radar cross section (RCS). Specific numeric examples are given in Table 1. A reduction in the RCS by 10 dB reduces the detection range by almost half.

The usefulness of a reduction in the radar-cross-section is even more apparent when viewed in the context of an electronic countermeasure (ECM) system. Typical ECM jamming is useful up to a distance where the radar power of the illuminating radar is high enough to "burn through" the ECM. This "burn through" range is directly proportional to the square root of the radar cross section of the aircraft. Table 2 shows that for a change in the radar cross section of 10 dB, the "burn through" range is reduced by more than half. Greater reduction gives even better performance.

Table 1

RCS Reduction dB	RCS Reduction %	Reduced Detection Range
10	90	0.56 R
15	97	0.42 R
20	99	0.32 R
25	99.7	0.24 R
30	99.9	0.18 R

Table 2

RCS Reduction dB	RCS Reduction %	Burn-through Range Normalized to an Untreated Target
10	90	0.32
15	97	0.18
20	99	0.10
25	99.7	0.06
30	99.9	0.03

Two significant points must be stressed concerning the above examples. Firstly, the examples concern only a scenario of an aircraft being detected by a radar. Radar-cross-section reduction techniques are applicable to more than just aircraft, even though the popular press stress its applicability mostly in those terms. The threat to naval vessels, tanks, AFVs and ground installations [3] from radar and radar guided munitions may be reduced by the judicious use of radar cross section reduction techniques.

Secondly, the reduction in the radar cross section of material must be regarded from a complete systems point of view. That is, it is not just the use of radar absorbing material that is necessary. The shape of the object must be considered, either in the original design stage, or when radar absorbing material is applied.

The strategic importance of radar absorbing materials has resulted in a high security classification being placed in projects associated with the "stealth" concept. This has meant that the majority of reports from commercial sources and Government laboratories have been classified, with the distribution limited in most cases to the country of origin. It is clear that some reports of direct relevance to Australian defence requirements have been published, but have not been made available to Australia [4]. Because of the security attached to information concerning radar absorbing materials, the latest developments might not be included in this review and advances in the field must be gleaned by inference from the limited amount of unclassified literature that is published.

One area that has proved useful in providing some information on recent advances in radar absorbing materials is the commercial sector where materials for anechoic chambers, microwave co-axial and waveguide devices and other areas have been discussed. The main drawback is that much of the information is of a proprietary nature and exact absorbing mechanisms and materials are not disclosed. However in many cases, the structure and nature of the absorbing material can be inferred.

In this report, the design, performance and selective uses of commercially available radar absorbing materials is considered. Possible developments in this field in terms of new absorption methods and materials are also addressed. An experimental procedure to measure the basic parameters of radar absorbing materials is described, from which the absorption, reflection and transmission properties of coatings may be obtained.

2. THEORY

When electromagnetic radiation is incident upon a material, it can undergo reflection, transmission and absorption. The various magnitudes of these quantities are dependent on the material properties and geometric factors such as size, shape etc. From a microscopic point of view, these interactions may be calculated quantum-mechanically from the atomic structure of the material. As the perspective of the interactions is changed from a microscopic level to a macroscopic one, different descriptions of the interaction process may be used, depending on the constituent properties of the material. The concept of homogeneity of the material may usually be considered in terms of the size of variations in the material matrix relative to the wavelength of the incoming radiation in the material. Therefore, at radar wavelengths, which typically range from centimetres to metres, many materials can be considered to act in a homogeneous manner, i.e. only the bulk macroscopic interaction processes need be considered. These processes are normally quantified in terms of the permittivity and permeability of the material. The permittivity describes the coupling of the electric component of the incoming radiation with the material, whilst the permeability describes the coupling with the magnetic component. Both these components can be represented by complex numbers, with the imaginary part being associated with the

loss or absorption in the material. If the coupling coefficients are known, then the reflection, transmission and absorption of a material may be calculated from Maxwell's equations with the appropriate boundary conditions applied.

The characterization of inhomogeneous materials in terms of such basic quantities is not simple. Inhomogeneties may be due to large, random scattering centres within the material in which case an appropriate scattering theory may be applicable. Large inclusions may act as a type of antenna at certain wavelengths. Theoretical aspects must be confined by a rigid specification of the number, size and type of inhomogeneity, and must be treated as a one-off situation.

In the next section, we consider the use as radar absorbing materials of what may be regarded at radar wavelengths as homogeneous materials which are characterized uniquely by permitivity and permeability. Only a brief outline of the general results for the interaction of electromagnetic radiation with absorbing media is presented in what follows, as a number of excellent reports exist [5, 6].

2.1 Layered Homogeneous Structures - Basic Theory

Consider plane wave radiation of a single frequency f incident upon a metal plate with a number N of parallel dielectric layers attached to it, as shown in figure 1. Each layer is characterized by its relative permittivity ϵ_m, and relative permeability μ_m, with a resistive sheet between each layer described by the normalized sheet conductance G_m relative to the free space admittance $1/Z_o$. It may be shown that the amplitude of the electric field of a positive going wave (i.e. away from the metal plate) in the m^{th} layer is [6].

$$B_m = \frac{e^{-ik_m x_{m-1}}}{2Y_m} [A_{m-1} (Y_m - Y_{m-1} - G_{m-1}) e^{-ik_{m-1} x_{m-1}} + B_{m-1} (Y_m + Y_{m-1} - G_{m-1}) e^{+ik_{m-1} x_{m-1}}] \quad (1)$$

Similarly, the amplitude of the negatively travelling wave in the m^{th} layer is

$$A_m = \frac{e^{-ik_m x_{m-1}}}{2Y_m} [A_{m-1} (Y_m + Y_{m-1} + G_{m-1}) e^{-ik_{m-1} x_{m-1}} + B_{m-1} (Y_m - Y_{m-1} + G_{m-1}) e^{+ik_{m-1} x_{m-1}}] \quad (2)$$

In the above equations, the following definitions apply;

$Y_m = \dfrac{\epsilon_m}{\mu_m}$	is the intrinsic relative admittance of the m^{th} layer
$k_m = \dfrac{2\pi}{\lambda_o} \epsilon_m \mu_m$	is the wavenumber in the m^{th} layer where λ_o is the freespace wavelength
G_m	is the sheet conductance of zero thickness between m & $(m+1)^{th}$ layer relative to $1/Z_o$

x_m is the position of boundary between m^{th} and $m + 1^{th}$ layers.

Equations (1) and (2) have been modified from those shown in reference [6] in that a generalized sheet conductance for the m^{th} layer has been added. Given an incident wave in free space, A_{N+1}, the reflection coefficient is simply

$$R = \frac{B_{N+1}}{A_{N+1}} \tag{3}$$

For values of A_1 and B_1 at the metal surface given as $B_1 = -1$, $A_1 = 1$, an iterative process may be used to calculate the A_{N+1} and B_{N+1} and hence the total reflection in free space as given by equation (3). The above equations and concepts will be used later in the report. Furthermore, we can also express the reflection in terms of the reflected power, defined as

$$|R_{dB}| = 20 \log_{10} |R|$$

2.2 Resonant Absorbers

One of the oldest types of absorbing structure is known as the Salisbury screen [7]. This consists of a thin sheet of resistive material spaced a certain distance ($x = d$) in front of a metal backing plate. The resistive sheet is usually some type of porous material impregnated with a lossy material such as carbon. Low loss spacing materials, like foams, plastics or honeycomb, are often used for structural rigidity.

Using the theory outlined in the previous section, a Salisbury Screen has $m = 2$ layers, the second layer being free space. From equation 1, the reflected wave B_2 is

$$B_2 = \frac{e^{ik_2 d}}{2Y_m} [A_1(Y_2 - Y_1 - G_1)e^{-ik_1 d} - B_1(Y_2 + Y_1 - G_1)e^{-ik_1 d}]$$

For a perfect metal reflector we have $B_1 = -A_1$ and therefore

$$B_2 = \frac{e^{-ik_2 d}}{2Y_m} B_1[(Y_2 - Y_1 - G_1)e^{-ik_1 d} - B_1(Y_2 + Y_1 - G_1)e^{+ik_1 d}]$$

Sufficient but not necessary conditions for $B_2 = 0$ are

$$Y_2 = G_1 \text{ (i.e. } G_1 = 1 \text{ because } Y_2 = 1)$$

and

$$e^{ik_1 d} + e^{-ik_1 d} = 0$$

i.e. $\cos k_1 d = 0$

from which

$$d = \frac{1}{\sqrt{\epsilon_1\mu_1}} [\frac{\lambda_0}{4} + \frac{n\lambda_0}{2}], \quad n = 0, 1, \ldots.$$

where λ_0 is the free space wavelengthg and μ_1 and ϵ_1 are real. Thus, zero reflectivity is obtained if an odd number of quarter waves separates the metal backing and a resistive sheet whose conductance is equal to the admittance of free space. It should be noted that the admittance of the spacer need not be the same as free space, provided that it is lossless.

One may regard the Salisbury screen in terms of transmission line. A lossless quarter wavelength transmission line transforms the short circuit at the metal plate to an open circuit at the resistive sheet. Zero reflection then occurs provided the resistive sheet is impedance-matched to free space. If there is imperfect matching, the reflectivity is no longer a minimum. Figure 2 shows the reflected power from a Salisbury screen with different resistive loads. Improved performance on terms of bandwidth may be obtained by stacking resistive sheets and spacers to form a multilayer system, with a gradual tapering in the value of the resistive loads G_m. This is known as a Jaumann absorber [8].

In the Salisbury screen and the Jaumann absorber the sheet itself is purely resistive. Imaginary components may be introduced by replacing the continuous resistive sheets with conducting materials deposited in appropriate geometrical patterns such as dipoles, crosses, etc [9-11]. These patterns may be defined in terms of their effective resistance, capacitance and inductance, thus enabling transmission line theory to predict the properties of a Salisbury screen containing these patterns. By a judicious choice of parameters, significant flexibility may be obtained in the design process.

A corollary of the Salisbury screen in magnetic terms offers distinct advantages in terms of the absorber thickness. In the Salisbury screen, the maximum in the electric field occurs at a quarter of an electric wavelength from the metal surface. The maximum in the magnetic field is immediately on the metal surface, so a lossy magnetic material placed directly on the material would be a good resonant absorber. The impedance of such a system may be derived from equations 1 and 2 as

$$Z_A = -iZ_0 [\sqrt{\frac{\mu_r}{\epsilon_r}} \tan [k_0 d \quad \epsilon_r\mu_r]]$$

where the subscript 0 refers to free space and the subscript r is the relative parameter in the absorbing material. When the argument of the tan is small, this equation becomes

$$Z_A = -iZ_0 \mu_r k_0 d$$

For a high magnetic loss material i.e. $\mu_r'' >> \mu_r'$ we obtain

$$Z_A = \frac{\mu_r'' \omega d Z_0}{c_o}$$

where c_o is the speed of light in vacuum, and $\omega = 2\pi/\lambda_o$.

For maximum absorption, the impedance of the absorber/metal plate system should match that of free space, which leads to the condition for the optimum thickness of the absorber as

$$d = \frac{c_o Z_o}{\mu_r '' \omega}$$

For example, the reflection coefficient for the above system ($\mu_r'' = 10$) at 10 GHz is zero when the thickness of the layer is only 0.477 mm. As is the case with the Salisbury screen, accurate control of the thickness of the absorbing medium needs to be maintained.

We now consider the case of a single dielectric layer of thickness d with no resistive sheet present. Using equation 3 with m = 2, $G_1 = 0$, $A_1 = 1$ and $B_1 = -1$ gives

$$R = e^{-i2d(k_1+k_2)} \left[\frac{(Y_2 - Y_1) - (Y_2 + Y_1)\, e^{-i2k_1 d}}{(Y_2 - Y_1) + (Y_2 + Y_1)\, e^{i2k_1 d}} \right]$$

In figure 3a, the reflected power is plotted against layer thickness, in this case expressed as d/λ_m, where λ_m is the wavelength is the material ($\lambda_m = \lambda_o \quad \epsilon_r \mu_r$).

For predominantly dielectric materials, $|\epsilon_r| > |\mu_r|$, maximum attenuation occurs around a quarter of an electric wavelength. The introduction of magnetic losses shifts the peak attenuation to about 0.3 and, more significantly, increases the bandwidth of the material. It is claimed that such a material is probably within current production capabilities of commercial RAM manufacturers for selected frequency ranges [12].

The perception changes when the same results are replotted against thickness in terms of the free space wavelength, as opposed to the wavelength in the material. The actual physical thickness of a magnetic/dielectric absorber is smaller than a dielectric absorber; and is much less than a quarter of the free space wavelength. We also note that when the conditions are perfectly matched (i.e. $\epsilon_r = \mu_r$), the reflected power decreases exponentially with thickness. When both ϵ_r and μ_r are real, i.e. no loss components, the magnitude of R will be unity, resulting in total reflection irrespective of the thickness d. When ϵ_r and μ_r are complex, the magnitude of R will vary as a function of d for any given values of ϵ_r and μ_r.

As is the case with a Salisbury screen, multiple dielectric layers may be used to increase the bandwidth of this type of absorber. Computer optimization schemes have been developed which provide the correct values of ϵ_m and μ_m to meet the design criteria [13, 14]. Of course, these value of ϵ_m and μ_m must be known prior to the design process. Because both the Salisbury screen and multilayer dielectric absorbers rely on interference between waves reflected from the front and back faces of the layers, they may be regarded as resonant absorbers. Hybrids of these two types of absorbers may also be designed to give enhanced performance.

In many practical situations, precise control over the thickness of an absorbing coating is difficult to maintain, as is the case when an absorbing paint is being applied. The previously described resonant absorbers rely on the thickness to be maintained accurately to ensure absorption at the design wavelength. The question of how to maximize absorption from non resonant absorbers then arises.

2.3 Broadband Absorbers

The reflection coefficient between free space and a half space absorber coating is simply

$$R = \frac{Z_A - 1}{Z_A + 1} \qquad (4)$$

where $Z_A = (\mu/\epsilon)^{1/2}$ is the relative impedance of the absorber. Reflection from this interface will be zero and all the energy in the incoming radiation will enter the absorber when $Z_A = -1$. Expressing μ and ϵ in terms of their complex parts $\mu = \mu' - i\mu''$ and $\epsilon = \epsilon' - i\epsilon''$ the loss tangents are defined as

$$\tan\delta_\mu = \frac{\mu''}{\mu'} = \text{magnetic loss tangent}$$

$$\tan\delta_\epsilon = \frac{\epsilon''}{\epsilon'} = \text{electric loss tangent}$$

The expression for the relative impedance may then be expressed as

$$Z_A = \left(\frac{\mu'}{\epsilon'}\right)^{1/2} \left[\frac{1 + i\tan\delta_\epsilon - i\tan\delta_\mu + \tan\delta_\epsilon\tan\delta_\mu}{1 + \tan^2\delta_\epsilon}\right]^{1/2}$$

This expression is equal to 1 (and the reflection coefficient equal to zero) when

$$\epsilon' = \mu' \quad \text{and} \quad \tan\delta_\mu = \tan\delta_\epsilon$$

Once the radiation has entered the material, the values of ϵ and μ must be as high as possible to ensure maximum absorption in the thinnest coating. This type of absorber has the exponential behaviour shown in the previous figure. Because these absorbers do not rely on a resonance effect, they have better broad band behaviour than a resonance absorber.

An improvement of the principle has been developed in what is commonly called a "graded dielectric absorber". In this case, a continuous gradation of the permittivity is used, with the permittivity at the front surface being close to that of free space, and increasing with depth into the material. This ensures that there are no sharp discontinuities in the material causing unwanted reflections, whilst giving values for the permittivity that give good absorption deeper into the material. This gradation of the dielectric may be obtained practically by either using gravity to control an absorbing compound soaking into a foam, or by dipping a base material into an absorbing material, with successive dippings to lesser depths. Another technique uses a geometric transition from free space to a high absorbing material to provide a dielectric gradient, as in the absorbers commonly used in radar anechoic chambers.

A specific form for this gradation in the permittivity profile that gives a specified reflection over a given frequency range and thickness has not, for a general case, been determined analytically, although a number of authors have studied a variety of different profiles. By assuming that the fractional change per unit length, with respect to a local wavelength $\lambda = \lambda_o(\epsilon_r)^{1/2}$ for non magnetic material, is a small constant, a, for all points within the layer, i.e.

$$a = \frac{\lambda_o}{2\pi} \frac{1}{(\epsilon)^{3/2}} \left[\frac{d\epsilon_r}{d\lambda}\right] << 1$$

Jacobs [15] obtained a dielectric variation of the form,

$$\epsilon_r(x) = \left[1 - \frac{\pi a}{\lambda} x\right]^{-2}$$

which minimizes the reflection coefficient. For a realistic type of dielectric variation [6], $\epsilon'(0) = 1$, $\epsilon'(d) = 400$, $\epsilon'' = 0.5$, a reflection coefficient of less than 0.1 may be obtained for thickness of $d/\lambda \geq 0.42$. Because Jacobs assumed in his analysis a matched impedance at the interface $x = d$, interference effects are ignored. With a metal backing at the interface, and a finite value of the permittivity next to it, interference effects could also become significant, to the extent that better performance than that predicted by an ideal Jacobs type layer has been obtained [16].

Other types of variation for the permittivity profile in a graded dielectric absorber include various linear and exponential profiles. A selection of these are shown graphically in figure 4 and in tabular form in table 3. In figure 4, the imaginary component of the permittivity for examples 6, 8 and 12 from table 3 are plotted. It is interesting to note that the minimum value of d/λ in these examples occurs in the case of the discontinuous function, whereas the two similar profiles give differing results. Intuitively, one would expect the opposite situation. A more complete discussion is to be found in reference 8.

This discussion of graded absorbers has ignored any contribution to the absorption process by the magnetic permeability. By postulating a functional form for both permittivity and permeability variation, even better performance, at even smaller layer thickness, could be obtained. However, the availability of materials that have the desired combination of properties is highly unlikely.

3. MODIFYING MATERIAL PROPERTIES

3.1 Additives

The previous sections have presented the theory of microwave absorption in both electrical and magnetic materials, for general values of the permittivity and permeability. The availability of real materials having the desirable properties of high absorption coupled with impedance matching to free space is quite limited. In this section we consider the theoretical aspects of combining two different materials to give the required electric and magnetic behaviour. As mentioned previously, we shall still confine ourselves to the case where the compound material may still be regarded as homogeneous at microwave frequencies.

Table 3 (after Ruck, reference 8)

Type of Variation	$\mu_r'(z)$	$u_r''(z)$	$\epsilon_r'(z)$	$\epsilon_r''(z)$	Minimum l/λ_o for $R < 0.1$
1. Ideal Jacobs	1	0	$(1 - z/l)^{-2}$	Small constant << 1	0.3
2. Finite Jacobs	1	0	$(1-0.95\ z/l)^{-2}$	1/2	0.42
3. Linear	1	0	1	$3\ z/l$	0.55
4. Linear	1	0	1	$6\ z/l$	0.77
5. Exponential	1	0	1	$3.76\ (z/l)^{1.5}$	0.4
6. Exponential	1	0	1	$0.285\ e^{2.73z/l}$	0.35
7. Exponential	1	0	1	$\frac{0.25}{l/\lambda_o}[6^{z/l} - 1]$	0.35
8. Exponential	1	0	$2^{z/l}$	$5^{z/l} - 1$	0.56
9. Exponential	1	0	$10^{z/l}$	$7^{z/l} -1$	0.68
10. Exponential	$3.3^{z/l}$	0	$50^{z/l}$	$0.3\ (3.3^{z/l} - 1)$	0.6
11. Exponential	$3.3^{z/l}$	$50^{z/l} - 1$	$50^{z/l}$	$0.3\ (3.3^{z/l} - 1)$	0.5
12. Three-layer discrete approximation to exponential	1	0	1 1.16 for 0.359 l 3.48 for 0.297 l	0.58 for 0.344 l	0.33

Additives to a supporting medium may take many forms, such as rods, wires, discs, spheres, etc. In the simplest case, based on the Lorentz method, a uniform electric field applied to a cubic array of metallic spheres embedded in a homogeneous dielectric supporting medium will induce a polarization in the small spheres. For non-interacting spheres (e.g. a low density of spheres) the modified permittivity of the compound material is

$$\epsilon = \epsilon_s \left(1 + \frac{\alpha N}{\epsilon_o}\right)$$

where ϵ_s is the permittivity of the supporting medium and N is the number of spheres per unit volume. The polarizability, α, depends on the shape of the additives, the material in the additive and the nature of the supporting medium. As the density of added spheres increases, interactions between spheres will start to influence the behaviour. For dipolar interactions, the permittivity of the compound system becomes

$$\epsilon = 1 + \frac{\alpha N/\epsilon_o}{1 - A\ (\alpha N/\epsilon_o)}$$

where A is a factor dependent on the relative positions of the added spheres [17]. With further increases in sphere density, higher order multipole interactions must be included in the above equations.

The effective permeability of these systems may also be modified. The relative permeability may be derived in terms of a magnetic polarizability of the individual additives. Techniques analogous to those outlined above may then be applied.

Calculations similar to those outlined above have been performed for systems containing small radar absorbing filaments fixed in a solid binder. The filaments were initially designed for use with radar absorbing chaff [18], and were modified to be absorbed in the binder material [19]. Conclusions reached in this and other papers [17] show that even for very high particle densities, higher order multi-pole interactions contribute only very little to the properties of the material. Also, the difficulty in calculating the polarizability of the additives is stressed in these reports.

This approach is not practicable in a real-world situation, due to the complexity of the model. Variables, in the form of the size distribution of the additives, the spatial distribution of the additives and their specific electrical and magnetic properties are too complex to specify for useful prediction. A more general relation between permittivity and density of additive has been determined by Lichtenecker [20] for dielectric mixtures, based on a stochastic mixture model [21]. Extending this work to the permeability of a mixture leads to the following relationships for the magnitude,

$$\log_{10}|\mu| = v \log_{10}|\mu_a|$$

and

$$\log_{10}|\epsilon| = v \log_{10}|\epsilon_a| = (1 - v) \log_{10}|\epsilon_o|$$

where the subscript, a, refers to properties of the additive, subscript, o, refers to the supporting medium, and v is the volume fraction of the additive. Dielectric and magnetic losses are related to the volume fraction by

$$\tan\delta_{\mu} = v \tan\delta_{\mu a} \text{ and } \tan\delta_{\epsilon} = v \tan\delta_{\epsilon a}$$

These results have been tested at MRL with a mixture of ferrite powder and epoxy resin. The results of figure 5, show that the above relationships are valid at least up to 50% volume fraction. Therefore, it is possible to tailor materials to have the desired permittivity and permeability, based on the required design criteria, given the respective permeability and permittivity of both the additive and supporting materials.

3.2 Non-Homogeneous Absorbers

The theory presented so far has concentrated on what may be regarded as homogeneous materials. As a rule of thumb, homogeneity may be regarded as applicable when the wavelength is larger by at least an order of magnitude than the cross sectional dimensions and spacings of the additives. When these limits are exceeded, the theory and interpretation of the physical processes is complicated greatly.

For example, consider the case in figure 6a where short brass metal fibres are added to a ferrite/rubber mixture [22]. The supporting ferrite/rubber compound will be a

lossy material, with absorption dependent on the ferrite type. The metal fibres will act as dipole antennas, absorbing incoming radiation at a frequency dependent on the length of the fibre. The fibres will reradiate at the same frequency, but in a highly non-specular manner, redirecting energy throughout the supporting compound [23]. This has the result of effectively increasing the path length of the incoming radiation in the ferrite/rubber mixture, increasing the total amount of absorption. For truly random distributions of added wires, the total interaction between the wire/ferrite/rubber mixture may still be characterized by an "effective" permeability and permitivity, allowing the design criteria specified in section 2 to be applied.

3.3 Hybrid Materials

A hierarchy of different absorption mechanisms has been built up in the previous sections, starting with simple resonant effects and leading to non-homogeneous materials. Each case has been treated in isolation to elucidate the physical processes used to obtain the desired bulk material properties with respect to microwave radiation. Many radar absorbing materials, both in use and under development, rely on a combination of mechanisms to achieve the desired behaviour.

For example, consider the system shown in figure 6a consisting of a metal plate, a wire/ferrite/rubber mixture as described in the previous section (layer A) and a ferrite/rubber mixture (layer B). The majority of the absorption of an incoming electromagnetic wave takes place in layer A, using the mechanisms outlined in the preceeding section. Layer B is designed so that it acts as a quarter wave impedance transformer between free space and layer A, by adjusting its permeability and permittivity by varying the ferrite content, and by changing the layer thickness. Results for this system under perpendicular polarization are shown in figure 6b. This absorbing system exhibits high absorption over a broad band across a wide range of incident angles. This type of absorber uses resonance effects, magnetic absorption, tailoring of the permeability and permittivity, and non-homogeneous additives to give this type of performance in very thin layers, typically less than 5 mm.

4. COMMERCIALLY-AVAILABLE MATERIAL

Worldwide, there are a number of manufacturers of radar absorbing materials. Each manufacturer offers many different types of absorber, each developed for a specific application. By far the majority of these materials are for strictly commercial use, as in anechoic chambers, interference suppression etc. For military uses, the number of materials freely advertised drops significantly. This is not to say that the materials have not been developed, only that their availability is often limited for security purposes. This section details a number of different types of commercially available radar absorbing materials. This is, by no means, meant to be a comprehensive list of all available materials. Rather it is an indication of the varied types of material on offer. Most commercial companies have the capability to develop new types of materials for specific application, and in some cases, offer full scale consultative facilities for customers with problems that require some type of radar absorbing material.

4.1 Surface Wave Absorbing Materials

The attenuation of fields generated by surface currents due to incident radar waves may be achieved by commercially available materials. SWAM [24], (surface wave absorbing material), manufactured by Plessey Materials of the UK is a magnetically loaded nitrite rubber. When placed in appropriate positions, relatively small amounts can reduce the radar cross section of an aircraft to a significant extent over the frequency range 1-10 GHz. As is the case for many broadband absorbers, some degree of attenuation will generally be available at higher frequencies. It is claimed [24] that SWAM is still effective up to 40 GHz. One relatively important characteristic of SWAM is its ability to absorb radiation when the angle of incidence is between 30-60° from normal, making it useful for the leading or trailing edges of aircraft.

4.2 Structural Absorbing Materials

In some situations it may be desirable to provide radar absorbing properties in a structural material. K-RAM [25] is a commercially available material composed of aramid fibres (kevlar) containing a lossy filler, backed by a carbon fibre laminate which acts as a reflector. The uses of structural radar absorbing material are fairly obvious such as on ground installations or the superstructure on ships, providing ballistic as well as radar protection. K-RAM can be manufactured to resonate at two or three frequency bands in the 2-40 GHz range. Typical performance figures for K-RAM are shown below and in figure 7.

Frequency Ranges (GHz)	Reflectivity (dB)
2-4 and 8-16	- 10
2-3.5 and 8.5-15	- 15
2.5-3.5 and 9-14	- 20

4.3 Camouflage Nets

Camouflage nets, which combine visual, infrared and radar camouflage, are being developed in many countries. One particular net, manufactured by the Swedish company Barracuda, contains a mesh of 10 μm stainless steel wires embedded in a plastic reinforcing material [26]. It is most likely that these wires act as radar scatters, rather than absorbers, although the plastic material may have some slight inherent absorbing properties. This material has undergone field trials in Australia to ascertain its usefulness on Army fuel tankers, where electrostatic discharge problems preclude the use of non-conducting nets. The manufacturers claim that this material will reduce specular reflection from metal surfaces by about 50%. Whilst this is not a large reduction it must be remembered that the material is for camouflage purposes. It is not always desirable to completely absorb radiation. What is often required is the ability to merge the return signal with that of the background.

4.4 Ferrite Absorbers

Ferrite materials have received much attention in the popular press because of the perceived application as a radar absorbing "paint". Commercially, ferrites have been utilized for many years in various absorbers, either as additives to absorbing rubber

materials [27, 28], as sintered ceramic tiles [29] or as sprays and paints [30]. The general structure of ferrites is that of the mineral spinel, $MeFe_2O_4$, where Me represents a divalent metal ion. The peaks in the loss spectrum in ferrites are due to spin resonances, and may be changed in frequency by substituting a portion of the Fe^{3+} ions with a divalent or tetravalent metal ion such as CO^{+2} or Ti^{+4}. The bandwidth of the loss mechanism is usually narrow, requiring the use of multilayer techniques similar to those employed for dielectric materials, when increased absorption bandwidth [13, 14] is needed.

Because ferrites are ceramic materials, they exhibit good performance both magnetically and mechanically at elevated temperatures up to their Curie point. Applications such as plasma spraying of aircraft engine intakes and components with a ferrite-thermal barrier combination would reduce the return signal obtained from aircraft engines - often a significant cause of reflections. Another example is Emerson and Cummings NZ series of sintered ferrite tiles [29]. These materials have been applied to towers, ships masts and aircraft, and may be designed to cover a broad frequency band. However, as with most ferrite materials, a large weight penalty may be incurred due to the material's high density.

4.5 Graded Dielectric Absorbers

This class of material offers many advantages when compared with ferrite materials, the main one being their light weight, making them particularly useful for aircraft. One example of this material is ADRAM - Advanced Radar Absorbing Material, manufactured by Plessey Materials [31]. It comes in the form of thin, flexible, carbon-loaded elastomeric sheets designed to be bonded to metallic surfaces. This material is fairly broadband (6 dB from 8-16 GHz, 15 dB from 10-12 GHz minimum). Less expensive types of graded dielectric absorber exist, usually consisting of a foam material. Usually these materials are not as robust in severe environmental conditions as ADRAM.

Another type of graded dielectric absorber is Plessey's External Netting Absorber (ENA). This is a lightweight, relatively low-cost, open-structured material with performance over a broad frequency band. At X-band, this material reduces the reflectivity by more than 20 dB. For broad band applications, 10 dB performance over the 6-100 GHz range is claimed [32]. This material, under the trade name RAM Panels, it currently in use with the Royal Navy. These panels consist of ENA encapsulated in a reinforced PVC envelope. In this form, the panel may be tied to any section of a vessel when the need arises. Being lightweight, it is easily folded away for storage when not in use. ENA is also being tested in Europe for use on the hanger doors of hardened aircraft shelters. By use of suitable backing materials, IR suppression of the signal from these shelters is also possible.

5. EXPERIMENTAL SYSTEMS

In section 2, it was shown that in principle it is relatively straightforward to design a radar absorbing material with desired characteristics particularly if coating thickness is not critical. The frequency, bandwidth and reflection characteristics may be tailored by a suitable choice of physical parameters. What is required as input to this design process is a database of electrical properties, i.e. the permittivity and permeability of representative absorbing materials.

Unfortunately, for many materials useful in radar absorbing materials, these electrical properties are either unknown across the desired frequency band, or are unavailable outside the company that developed them. This is particularly true for many of the newer types of absorbers. It is necessary therefore in any study of radar absorbing materials to be able to accurately measure the complex permeability and permittivity of materials, or any combination of materials.

For existing commercial radar absorbers, or for systems that are highly inhomogeneous, i.e. those which cannot be characterised simply in terms of ϵ and μ, it is often unnecessary or impractical to measure these basic properties. Simple free space reflectivity measurements using small test panels are often satisfactory to characterise a sample. For materials that rely on scattering of the microwave radiation, free-space experiments to measure the angular distribution of the scattered field must be made.

5.1 Electrical and Magnetic Properties

Most measurement methods described in the literature only yield permittivity mainly because relatively few classes of materials are magnetic. However, it is usually possible to modify these methods to also measure the permeability [33].

A number of different techniques to measure the electric and magnetic properties have been developed. Resonance methods rely on the fact that the resonant frequency of a cavity will change with the insertion of material into the cavity, the resonant frequency being determined by the dimension of the unfilled cavity. It is then possible to infer the electrical properties of the inserted material. This technique is limited in that only one frequency may be measured at a time. Measurement over a range of frequency would require a number of cavities of different size.

A second method often employed is Time Domain Spectroscopy. In this technique, a short pulse is transmitted down a transmission line which contains a small sample of the material to be measured. From the Fourier transforms of both the input and response waveforms, the permeability and permittivity of the sample may be calculated. Whilst being a technique which in principle will measure permeability and permittivity over a large frequency band, practical consideration in terms of timing and equipment limits this technique to the range 100 MHz to 3 GHz.

The most general method is the transmission line technique, in which the sample is placed inside the transmission line. The structure of the field within the transmission line is well characterised, and all energy used in the measurement is confined within the system. The sample must be machined accurately to fit into the transmission line to ensure good electrical contact. Figure 8 shows two types of sample holders often used in these experiments, one for X-band waveguide and the other for 7 mm beadless coaxial airline.

The experimental technique used to measure both permittivity and permeability was first described just after World War II [34], and was the standard method employed for many years. However, advances in microwave instrumentation and computer technology has greatly enhanced the measurement process.

Figure 9 is the complete schematic representation of the experimental system used at MRL. A HP8510 Network Analyser is used to control the system. This unit can measure error-corrected magnitude, phase and group delay from 500 MHz to 18 GHz. The scattering function S_{11} and S_{21}, corresponding to the reflection and transmission, are the usual way of specifying these functions. The error-correction model employed removes systematic errors such as directivity, source mismatch, load mismatch, crosstalk and

frequency response. The transformation from the scattering functions S_{11} and S_{21} to the permittivity and permeability is well documented and is facilitated by the aid of an external computer [35].

5.2 Free-Space Measurements

Accurate and unambiguous free space measurements require just that; a free space outdoor range. This, in many cases, is impractical. Techniques to simulate a free space environment have been developed over the years. The NRL arch is a good laboratory scale system which, with good experimental controls, yields accurate results [36].

More accurate results may be obtained from a radar anechoic chamber. However, these are expensive and could only be justified if a wide range of measurements were performed in them. Electromagnetics Group, part of the Surveillance Research Laboratory, DSTO Salisbury, has excellent facilities for measuring radar cross sections, antenna radiation patterns and absorption properties of materials.

At MRL, a system similar to the NRL arch has been developed for initial testing of samples. This system will allow approximate free space, bistatic reflection measurements to be made over a wide frequency range. When necessary the results may be cross checked with the Surveillance Research Laboratory anechoic chamber to ensure accuracy.

As in the previous section, a HP8510 Network Analyser is used with the same error correction technique being applied [37]. Some radar absorbing material is used in the measurement facility to reduce spurious reflections from the room. In addition, pseudo time-gating using Fourier transform techniques, may be used to reduce reflection effects due to the room.

Figure 10 shows the bistatic of measurement system used at MRL. The samples are placed on polystyrene support stands to reduce extraneous return signals. Calibration is performed by using a flat metal plate exactly the same size as the sample. Samples of any practical size may be measured although 15 cm x 15 cm is the normal size used. The distance between the sample and the horn antennas is varied according to the waveband used and the sample size, to ensure primarily that a plane wave is incident on the sample, and also that edge effects from the sample are minimised. Figure 11 shows the reduction in reflection power due to a Plessey absorbing material measured at X-band frequencies.

6. CONCLUSION

Radar absorbing materials may be broadly separated in two categories, resonant absorbers and broadband absorbers. Resonant absorbers are based on interference effects and thus only work at one or two frequencies. They also require strict control over layer thickness. Broadband absorbers rely on the inherent loss in the material which composes the layer, and therefore do not rely so stringently on thickness. In reality, a combination of broadband and resonance effects contribute to the total reduction in the return signal from a material.

Design principles that lead to a specified performance with respect to reflection coefficient, wavelength and layer thickness have been stated. The knowledge of permittivity and permeability values over a broad frequency range is an essential input into

these design calculations. Experimental techniques to establish these parameters are described, as well as experimental verification techniques for testing the final coating.

Methods of modifying electrical and magnetic properties are reviewed. Homogeneous and non-homogeneous additives may be used to modify material properties to give the desired performance.

A brief survey of the common classes of commercially available radar absorbing materials is made, with a number of references to specific materials.

7. REFERENCES

1. Stepanov, Y.G. (1968). Antiradar camouflage techniques, Chapters 3-4 in Protivo-Radiolokatsionnya Maskirova, Soviet Radio Publishing House, Moscow, pp. 44-84. Washington, DC: Joint Publications Research Service JPRS, 47734.

2. Sweetman, W. (1985). The vanishing airforce. International Defence Review, 8.

3. Dawson, M.H. and Rechlin, F.F. (1973). Microwave analysis of the terrain reflector camouflage concept (Technical Report LWL-CR-25C73). US Army Land Warfare Laboratory.

4. Kuch, C.M. F-18 radar cross section reduction (RCSR) investigations, Phase IIa. RCSR Measurements, Vols. i and ii, NADC-77106-20, December 1977 - July 1979. This report has not yet been obtained by the author. It is included as an example of the type of information available from US sources. At the time of writing, nearly 200 classified US reports were found in a database search. (SECRET)

5. Doig, J.A. (1984). Theoretical analysis of reflection of radio waves from radar absorbing coatings (ERL-0307-TM). Salisbury, SA: Electronics Research Laboratory.

6. Knott, E.F., Shaefler, J.F. and Tuley, M.T. (1985). Radar cross section. Artech House, Washington, Chapter 8.

7. Salisbury, W.W. (1952). Absorbent body for electromagnetic waves. US Patent No. 2599, 944, June 10, 1952.

8. Ruck, G.T. (Ed.) (1970). Radar cross section handbook. Vol. II, Ch. 8, New York: Plenum Pressm.

9. Meyer, E. and Severein, H. (1956). Absorption devices for electromagnetic waves and their acoustic analogues. Z. Ange. Phys., **8**, pp. 105-114.

10. Chen, C.C. (1975). Transmission through a conducting screen perforated with apertures. IEEE Transactions on Microwave Theory Techniques, **MTT-18**, pp. 627-632.

11. Pelton, E.L. and Monk, B.A. (1979). Scattering from periodic arrays of crossed dipoles. IEEE Transactions on Antennas Propag, **AP-27**, pp. 323-330.

12. Knott, E.F. (1979). The thickness criterion for single-layer radar absorbents, IEEE Transactions, **AP-27**, pp. 698-701.

13. Amin, M.B. and James, J.R. (1981). Techniques for utilization of hexagonal ferrites in radar absorbers, Part 1, Broadband planar coatings, The Radio and Electronic Engineer, **51** (5), pp. 209-225.

14. Amin, M.B. and James, J.R. (1981). Techniques for ytilization of hexagonal ferrites in radar absorbers, Part 2, Reduction of radar cross-section of HF and VHF wire antenna, Radio and Electronic Engineer, **51**, (5), pp. 209-225.

15. Jacobs, I. (1958). The non-uniform transmission line as a broadband termination, Bell System Technical Journal, **37**, p. 913.

16. Franceschetti, G. (1964). Scattering from plane layered media, IEEE Transactions **AP-12**, p. 754.

17. Kharadly, M.M.Z. and Jackson, W. (1953). The properties of artificial dielectrics comprising arrays of conducting elements, Proceedings of the Institution of Electrical Engineers, **111** (100), pp. 199-212.

18. Swinford, N.W. (1975). Electromagnetic behaviour of radar absorbing chaff, (Technical Note 354-43). China Lake: Naval Weapons Centre.

19. Gauss, A. A new type of EM wave absorbing coating. Ballistic Research Laboratory, June 1982.

20. Lichtenecker, K. (1918). On the resistance of certain novel conductors, Phys Z., **19**, p. 374.

21. Neelakantaswamy, P.A., Chowdar, B.V.R. and Rajharatnam, A. (1983). Estimation of permittivity of a compact crystal by dielectric measurement of As powder, Journal of Physics D : Applied Physics, **16**, pp. 1785-1799.

22. Hatakeyama, K. and Inui, T. (1984). Ferrite electromagnetic wave absorber composed of short metal fibres and its applications. In Electromagnetic Compatibility, International Conference, Tokyo, Japan 1984, pp. 504-508.

23. Chen To Tai. (1984). Dipoles and monopoles. In (ed.) R.C. Johnson and H. Jasik Antenna engineering handbook, 2nd Edition, New York: McGraw-Hill.

24. Plessey Technical Bulletin, Swam microwave absorber, Plessey Materials, Towcester, UK.

25. Plessey Technical Bulletin, K-RAM - A structural radar absorbent material, Plessey Materials, Towcester, UK.

26. Diab Barracuda AB, Data Sheet, Stockholm, Sweden.

27. Gupta, S.S. and Srivastava, N.C. (1979). Physics of microwave reflection at a dielectric-ferrite interface. Physics Review B, **19** (10), pp. 5003-5412.

28. Ueno, R., Ogasawara, N. and Inui, T. (1980). Ferrite or iron oxide impregnated plastics serving as radio wave suppressors. In Ferrites: Proceedings of the International Conference, September-October 1980, Japan, pp. 890-893.

29. Emerson and Cumming Technical Bulletin 8-2-17, Eccosorb NZ.

30. Plessey Materials, Private Communication.

31. Plessey Technical Bulletin, ADRAM - lightweight microwave absorber, Plessey Materials, Towcester, UK.

32. Plessey Technical Bulletin, ENA - external netting absorber, Plessey Materials, Towcester, UK.

33. Lederer, P.G. (1986). An introduction to radar absorbent materials (Report No. 85016). Royal Signals and Radar Establishment.

34. Birks, J.B. (1948). Proceedings of the Physical Society (London), **60**, pp. 282-292.

35. Hewlett-Packard Product Note 8510-3, Measuring thc dielectric constant with the HP 8510 network analyser.

36. Reference 6, Chapter 9, pp. 296-297.

37. Hewlett Packard Product Note 8510-2, Radar cross section measurements with the HP 8510 network analyser.

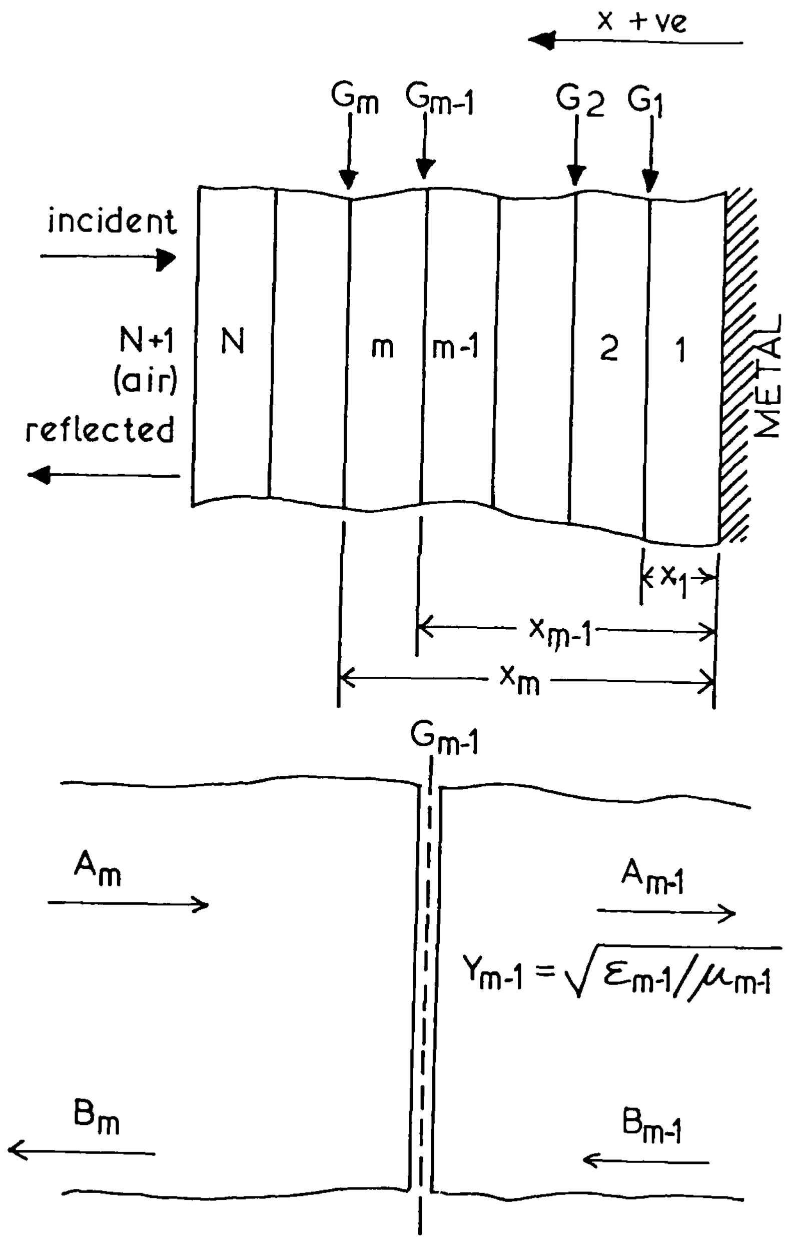


Figure 1 *Schematic representation of the relationships between materials properties and physical dimensions for a multilayer system.*

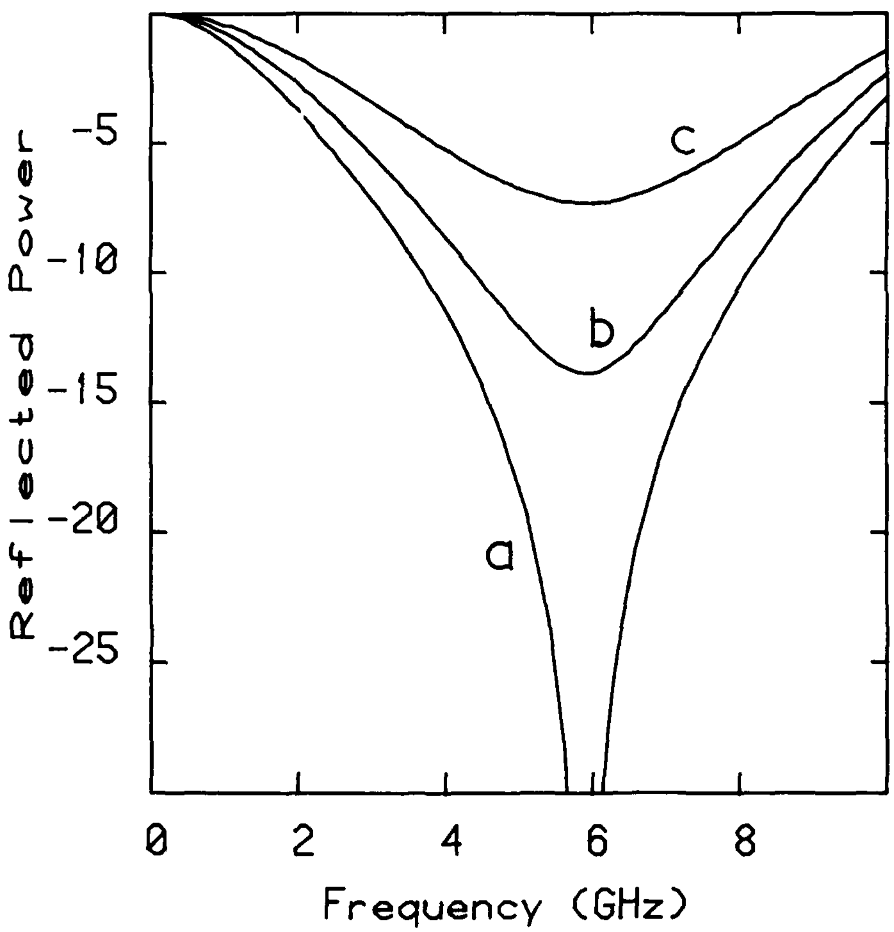


Figure 2 Reflected power from a Salisbury Screen. with sheet resistivity of (a) 377 Ω (b) 250 Ω (c) 150 Ω

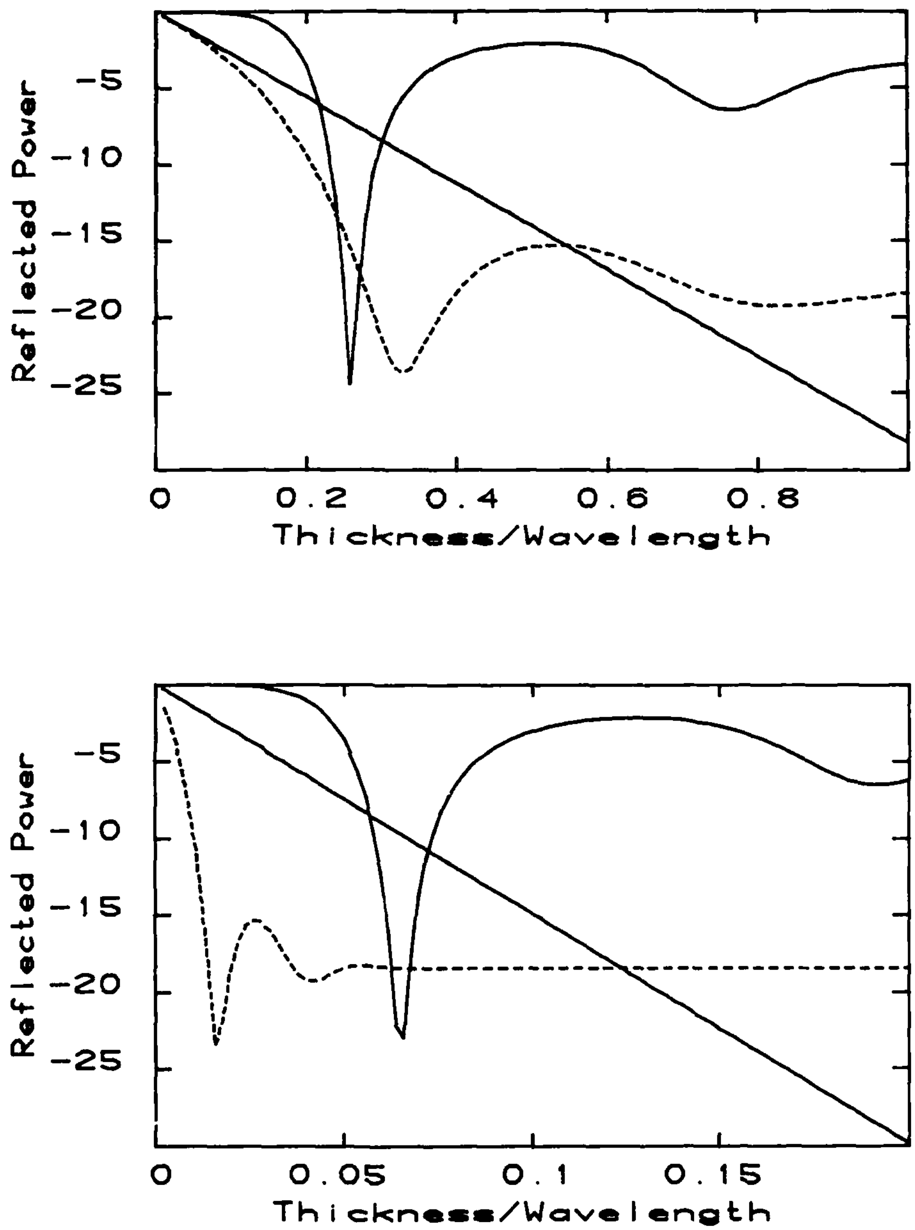


Figure 3 — *Reflectivity curves against electrical thickness (d/λ , top graph) and actual thickness (d/λ_o, lower graph)*

Dash line $|\epsilon| = 25$, $|\mu| = 16$, $\delta_\epsilon = 30°$, $\delta_\mu = 20°$
Solid line $|\epsilon| = 16$, $|\mu| = 1$, $\delta_\epsilon = 20°$, $\delta_\mu = 0°$
Straight line $|\epsilon| = |\mu| = 4$, $\delta_\epsilon = \delta_\mu = 20°$

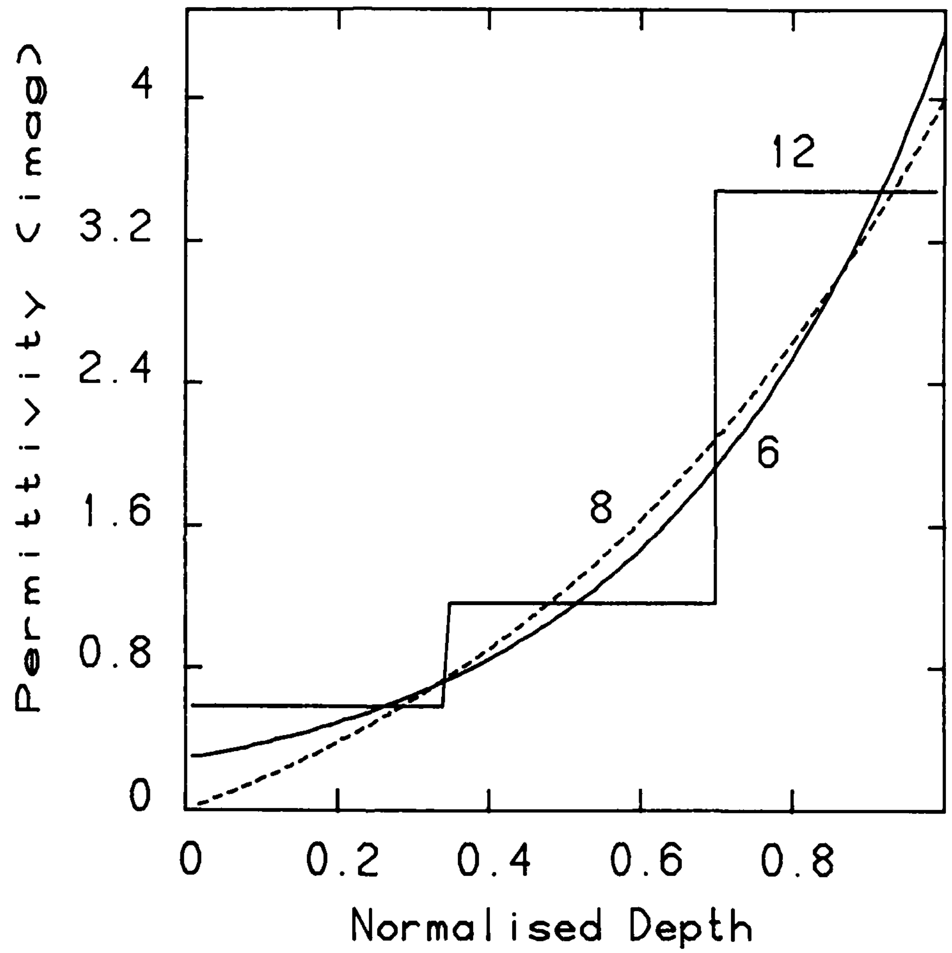
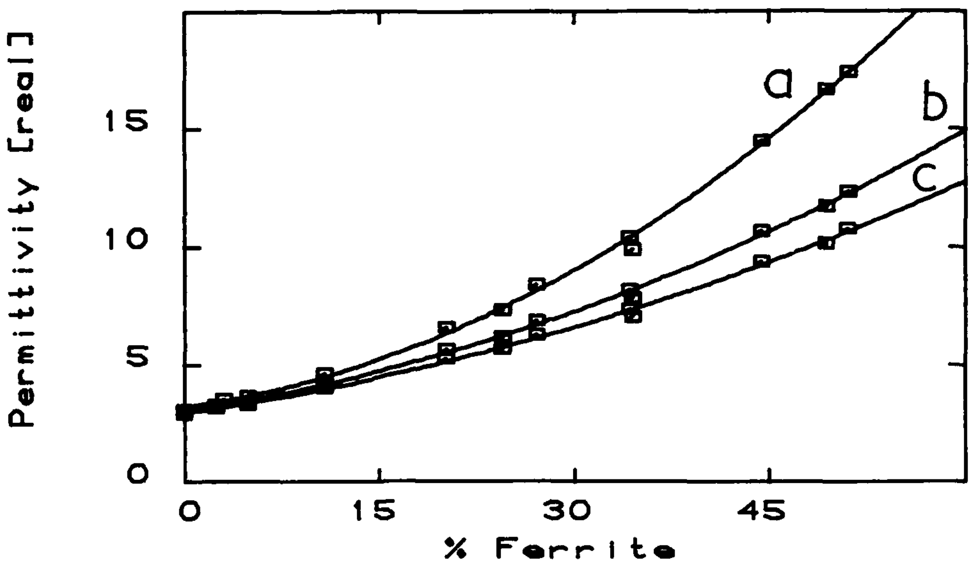


Figure 4 *Imaginary part of the permittivity profile for models 6, 8 and 13 of table 3.*



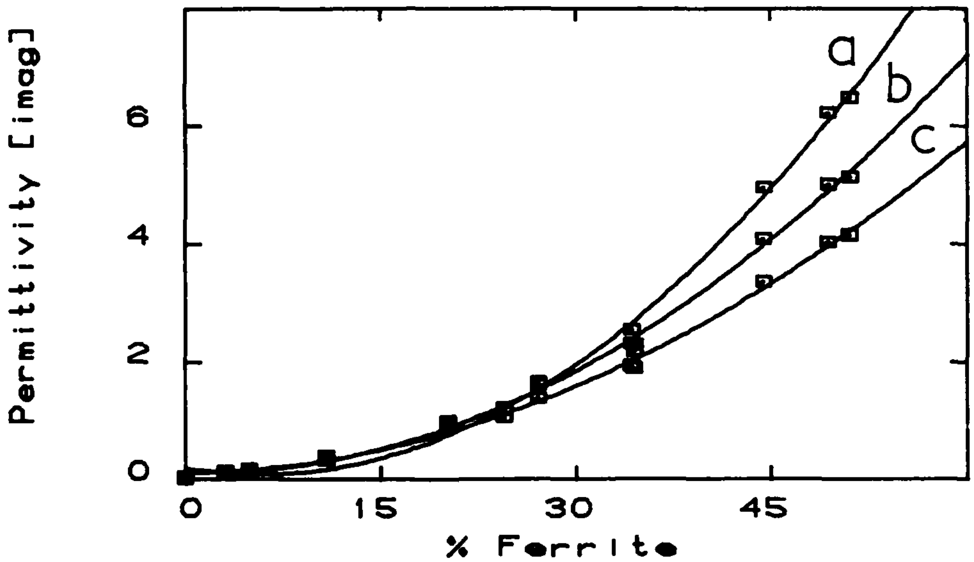


Figure 5 *Real and imaginary components of the permittivity for a ferrite/epoxy mixture, as a function of ferrite percentage composition.*
(a) 0.5 GHz (b) 2.5 GHz (c) 4.5 GHz

Figure 6(a) *Hybrid Absorber Layer A : ferrite/chloroprene-rubber/3mm brass fibre*
: 68.95/29.55/1.5 percentage composition
: thickness = 1.3mm
Layer B : ferrite/chloroprene rubber
: 20/80 percentage composition
: thickness = 3.3mm

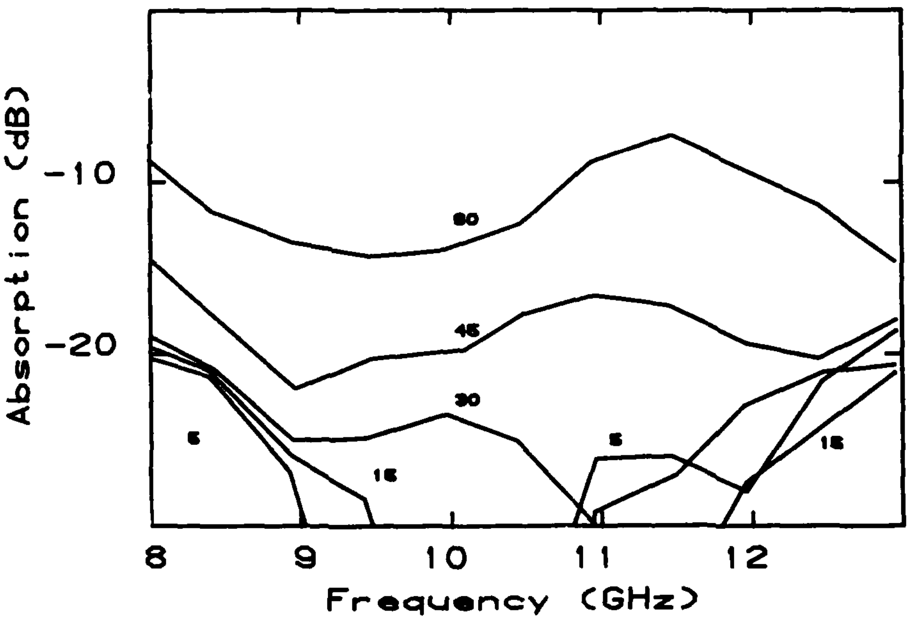


Figure 6(b) *Absorption of a hybrid absorber as a function of frequency. The numbers on each curve indicate the detection angle*

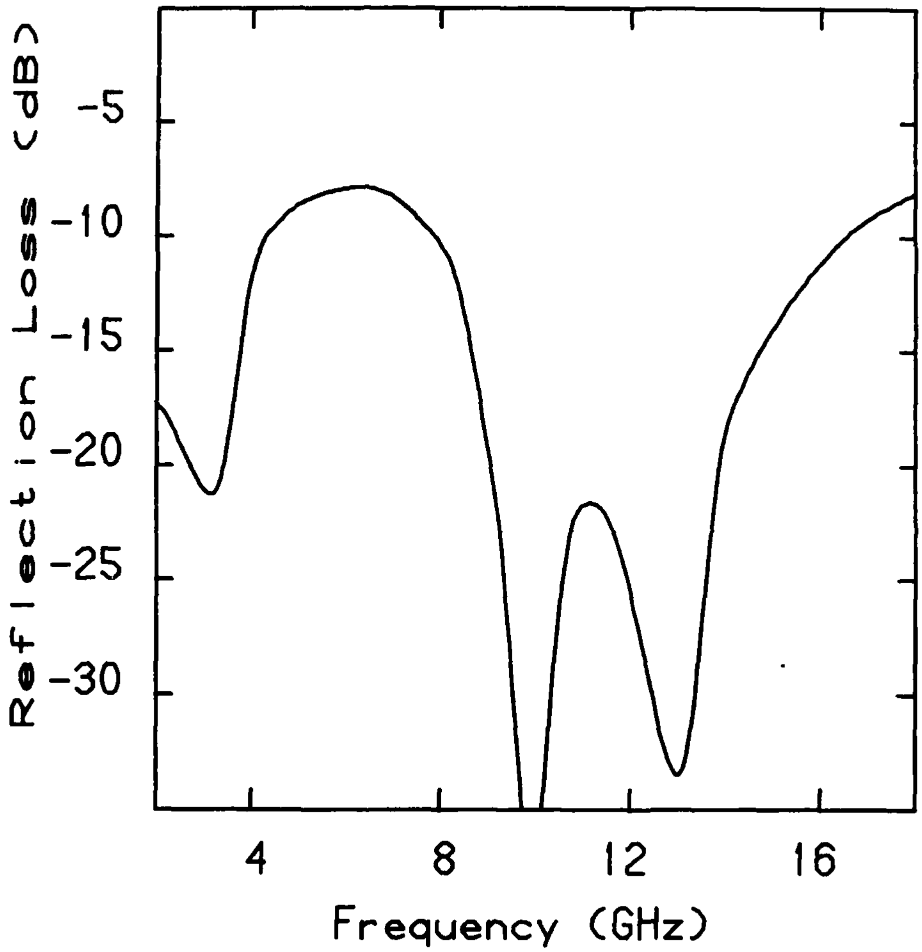


Figure 7 *K-RAM triple band structural absorbing material.*

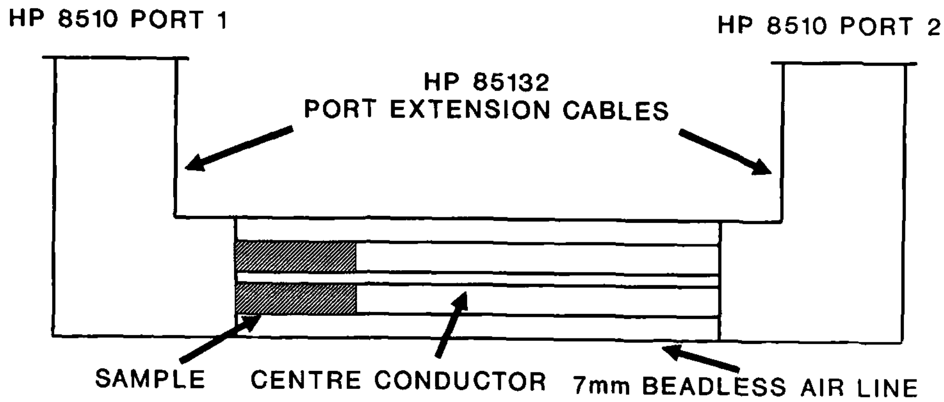


Figure 8(a) Co-axial sample holder and connections

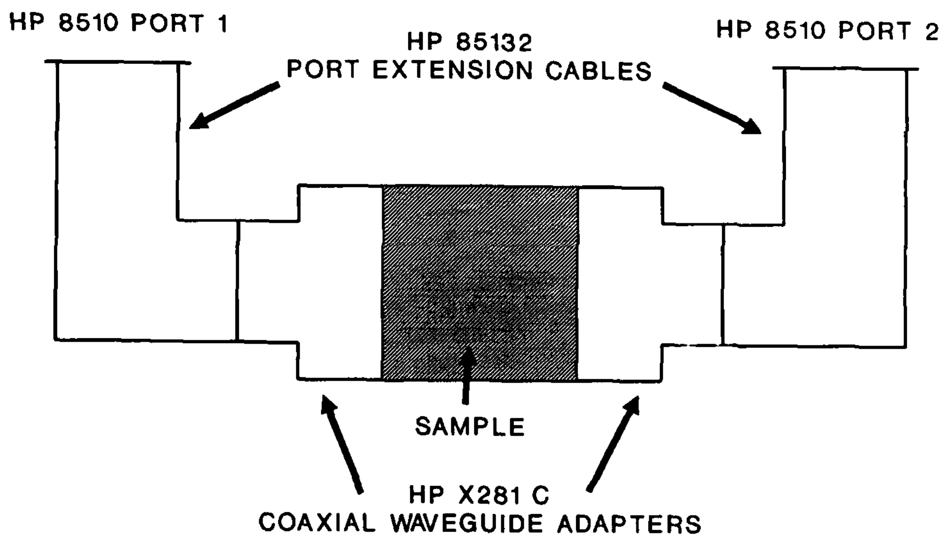


Figure 8(b) Waveguide sample holder and connections

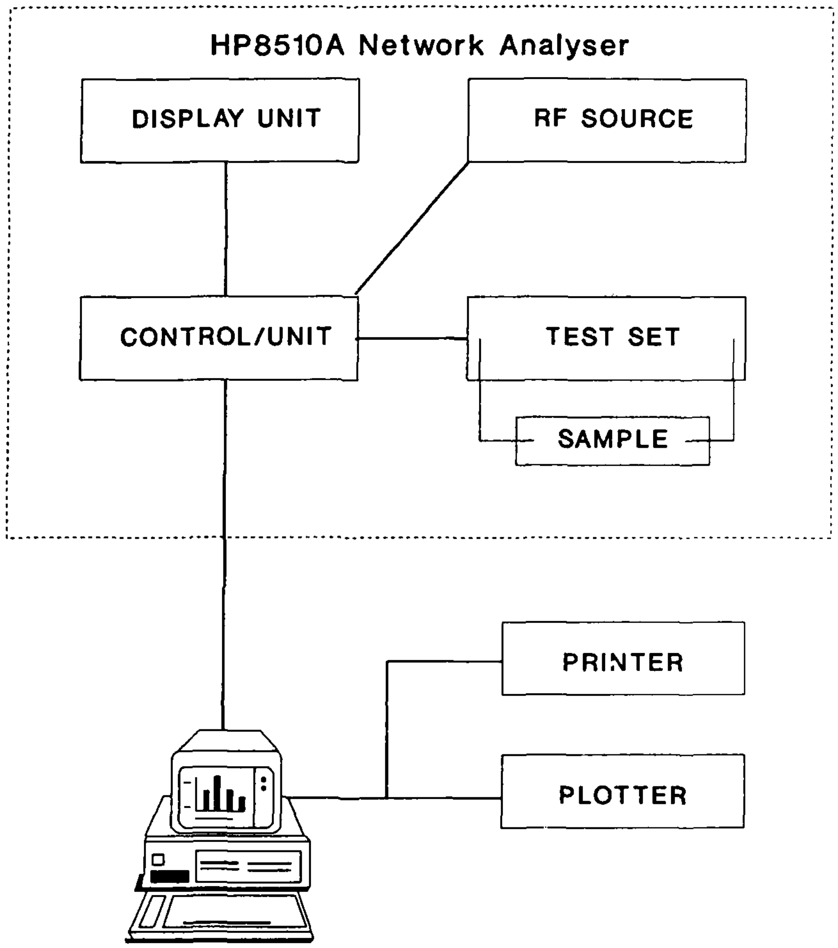


Figure 9 *Experimental system to measure the complex permittivity and permeability.*

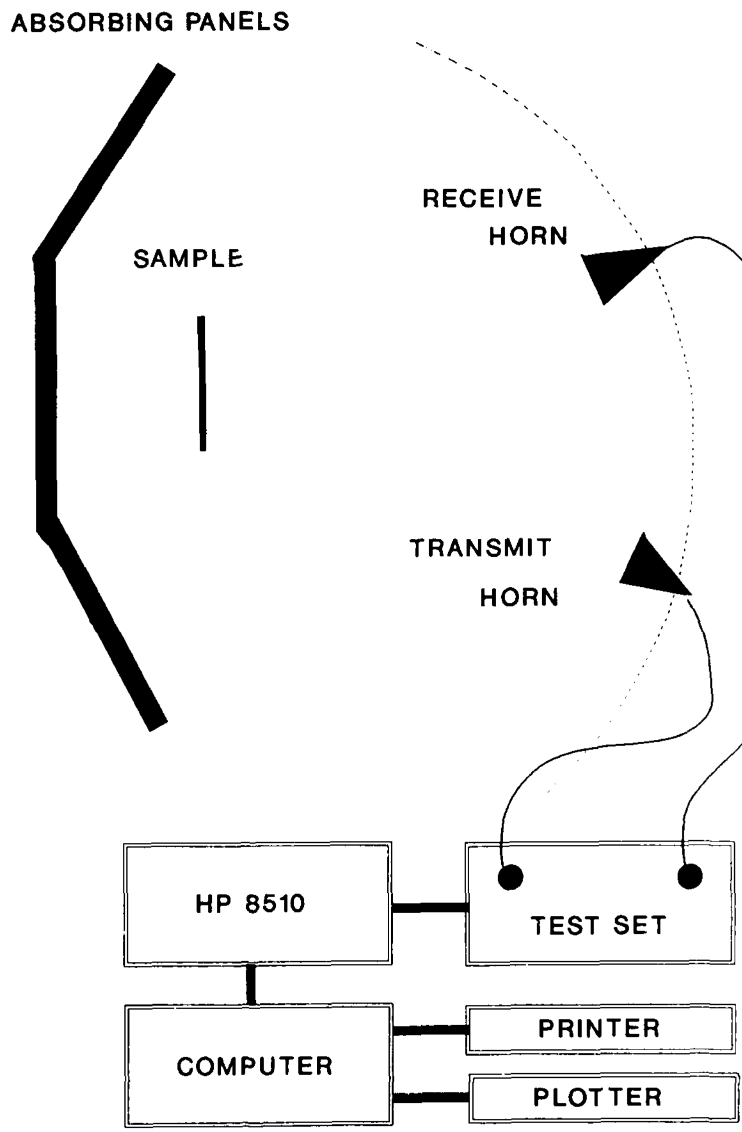


Figure 10 Experimental Setup for Measuring the Free Space Reflectivity of Large Samples

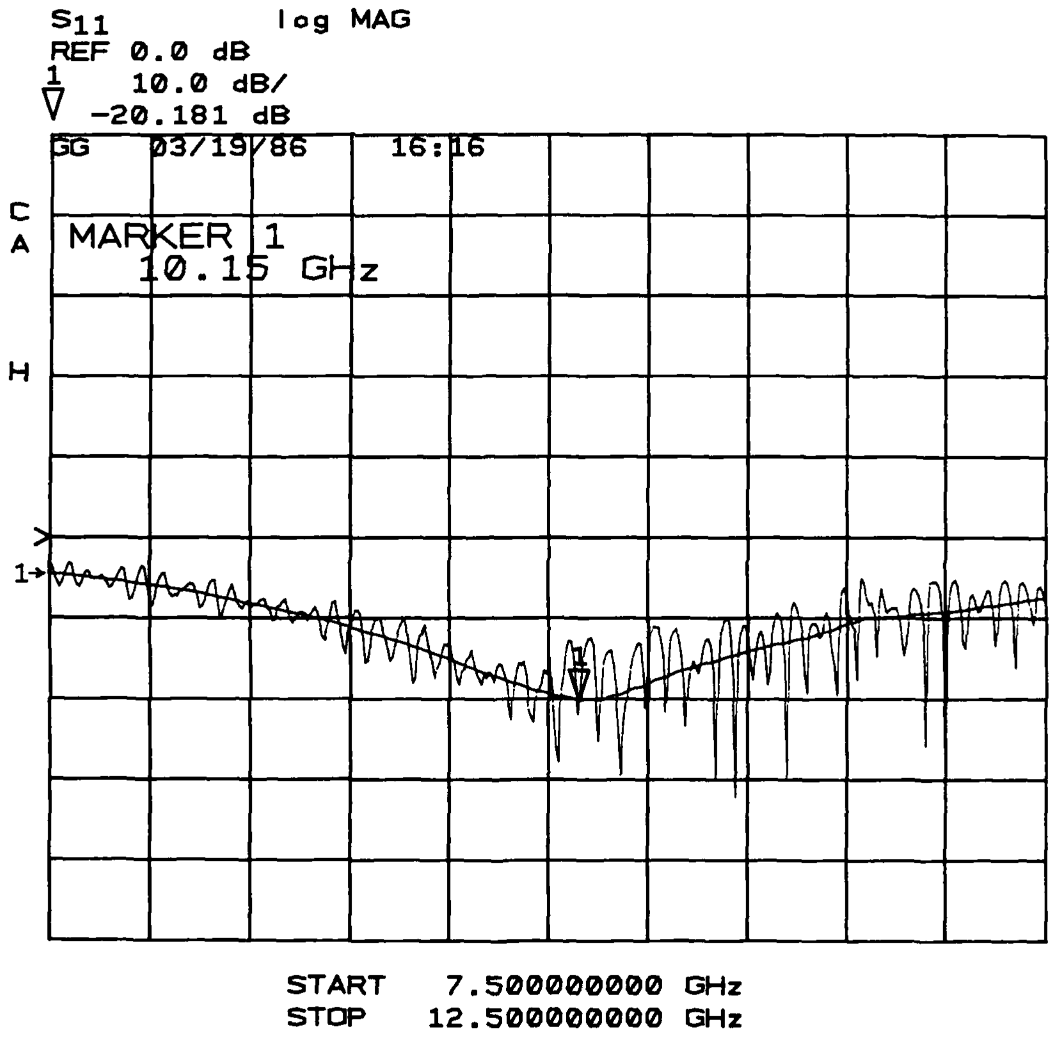


Figure 11 *Experimental attenuation measured for a Plessey absorber, showing the effect of the Fourier transformation on the original data.*

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ABSTRACT

This Report gives an introduction to the theoretical basis for the design of radar absorbing materials (RAM) with emphasis given to techniques for modifying material properties to give the desired performance. These techniques include additives in the form of scatterers, loops, antennae and graded absorbers. A brief survey of the more common types of commercially available radar absorbing material is given. Experimental methods for measuring and testing these materials are described.

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